

# **STUDY OF AUTOMATED MODULE FABRICATION FOR LIGHTWEIGHT SOLAR BLANKET UTILIZATION**

## **Final Report**

**TRW 79.5536.3-06**

**(NASA-CR-162157) STUDY OF AUTOMATED MODULE  
FABRICATION FOR LIGHTWEIGHT SOLAR BLANKET  
UTILIZATION Final Report (TRW Systems  
Group) 79 p HC A05/MF A01**

**N79-31763**

**CSCL 10A**

**G3/44 Unclas  
31887**

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**PREPARED UNDEF. CONTRACT NO. 955205 FOR  
THE JET PROPULSION LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA**

**"This work was performed for the Jet Propulsion  
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TECHNICAL CONTENT STATEMENT

"This report contains information prepared by TRW Defense and Space Systems Group under JPL subcontract. Its content is not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or the National Aeronautics and Space Administration."

**ABSTRACT**

"Study of Automated Module Fabrication for Lightweight Solar Blanket Utilization" describes cost-effective automated techniques for accomplishing the titled purpose; based on existing in-house capability.

This eight-month study used as a measure of the considered automation the production of a 50 kilowatt solar array blanket, exclusive of support and deployment structure, within an eight-month fabrication period; a greatly accelerated pace by today's standards. Solar cells considered for this blanket were  $2 \times 4 \times .02$  cm wrap-around cells,  $2 \times 2 \times .005$  cm and  $3 \times 3 \times .005$  cm standard bar contact thin cells, all welded contacts.

Existing fabrication processes are described, the rationale for each process is discussed, and the capability for further automation is discussed.

Conclusions are: (1) Because of existing in-house automation, the 50 kw 8-month fabrication could be done on a three shift basis, thereby illustrating one merit of automation: increased range of production capacity; (2) Attrition from human handling of thin cells makes automation practically mandatory; (3) Labor cost reductions are large enough to attract private investment in the automated equipment; (4) The 50 kw 8 month market size is sufficient for making the incremental automation investment of one-half to one million dollars highly attractive to TRW.

The blanket utilizing  $3 \times 3 \times .005$  cm cells has the best power-to-mass ratio of 254 w/kg and is lower in cost than the  $2 \times 2 \times .005$  cm blanket.

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## 1.0 SUMMARY

### 1.1 General

TRW Power Source Manufacturing Department has completed an eight-month program entitled "Study of Automated Module Fabrication of Lightweight Solar Blanket Utilization" on JPL Contract 955205 to recommend cost-effective automated techniques for fabricating space photovoltaic blankets, based on existing in-house automated assembly capability. A blanket is defined as a solar array and substrate not including major structural supporting and extending mechanisms.

### 1.2 The Process

The present capability consists of stand-alone automated process operations, with storage between, rather than a conveyor-belt system with all operations linked together. The stand-alone approach provides a high degree of flexibility for meeting different production schedules for differing solar array configurations and for improving the productivity of one station at a time. The cell storage system projected in this study consists of large-capacity slotted magazines, similar to slide trays, designed to interface with each operation. The module handling system consists of precision assembly and transfer fixtures and vacuum pick-up frames. The goal is to eliminate handling by workers of units smaller than a magazine, a fixture, or a frame while individual cells are handled only by automated machines. Modules of cell sub-arrays are mated to the flexible substrate thereby forming panels which are then joined to form a blanket.

Coverglass would be applied automatically to wrap-around cells using DC93-500 silicone adhesive. These cells would then be placed face down in precision assembly fixtures, strings of suitably designed inter-connectors would be added, and all of the welds would be made and tested automatically, thereby forming a module.

Interconnectors would be welded automatically to the front contacts of the thin standard bar contact cells individually before the cover-glass is applied, all other operations being the same as those described in the preceding paragraph.

Further automation of these operations to increase their throughput limits is practical and would cost between one-half and one million dollars.

### 1.3 The Photovoltaic Blanket Assemblies

In order to measure the present and projected levels of automation, a greatly accelerated fabrication pace by today's standards was considered:

- The solar cell array blanket was fifty (50) kw operating at 55°C in earth orbit.
- The solar array blanket was to be completed in eight months.
- The blanket was sized at 381 feet long x 12 feet wide, consisting of 155 panels, each 30 inches x 12 feet in size.
- The panel is made up of eight (8) modules 15 inches x 36 inches in size each produced automatically.

- Three types of solar cells were considered: 2 x 4 x .02 cm wrap-around contact; 2 x 2 x 0.005 cm and 3 x 3 x 0.005 cm standard bar contact; all 11% efficient.

It was found that, even with such an accelerated hypothetical production rate the present TRW facility could handle it if the production line were to be operated on two and a half shifts, leaving a very thin margin for equipment shut-downs or maintenance. A Near-Term Automated Capability was projected, requiring a very small capital investment, resulting in a facility which could operate on a comfortable two-shift basis reducing fabrication cost by 30%. An Optimized Future Automation was projected which required the capital investment mentioned earlier, resulted in essentially a one-shift operation, and reduced fabrication costs by 70% from present value. Since these reductions represent several million dollars, automation is economically justified.

#### 1.4 The Inspection Problem

This comparison also revealed a bottleneck which would occur due to lack of automation in the quality assurance inspection which generally follows each fabrication step. A cursory survey revealed that there are many automated inspection approaches available, but the detailed study leading to proper selection of such equipment was outside of the scope of this program.

### 1.5 The Conclusions

The study showed that the "Future Optimized Automated" total cost of the blanket was lowest using the  $2 \times 4 \times .02$  cm wrap-around contact cell, 1.5 times higher using the  $3 \times 3 \times .005$  cm cell, and 1.6 times higher using the  $2 \times 2 \times .005$  cm cell.

The power-to-mass ratios were estimated to be 140 watts/kg for the blanket using the  $2 \times 4 \times .002$  cm cells, 246 watts/kg using the  $2 \times 2 \times .005$  cm cells and 254 watts/kg for the blanket using the  $3 \times 3 \times .005$  cm cells.

From several related cost-benefit analyses, the market necessary to support the capital investment for the future automation is estimated to be fifty (50) kw over a time period of eight months.

It was concluded that automation is cost-effective, it is practically mandatory for reduced attrition of thin cells and it increases probable reliability of the array blanket.

### 1.6 The Recommendations

There are two (2) major recommendations: (1) Automated inspection methods must be studied and cost-effectively incorporated into automated fabrication operations in order to maintain the high through-put rates and reliability required and (2) cost-effective automation must be implemented wherever large-scale solar blankets are to be built in the future not only from the results of this study but additionally because both larger conventional cells ( $5 \times 5 \times .02$  cm) and promising

innovative thin cells, (Front Surface Field and Thin Tandem Junction) of the future will require automated handling to maintain low attrition rates during array fabrication.

## 2.0 INTRODUCTION

This report describes the results of an eight-month study conducted by TRW under JPL contract #955205 entitled "Study of Automated Module Fabrication for Lightweight Solar Blanket Utilization". The study provides pertinent information on the appropriate cost-effective automated fabrication techniques required to produce large lightweight space photovoltaic blankets. A photovoltaic blanket is defined as a solar array including substrate but excluding the major structural supporting and extending mechanisms. The basis for the study was the existing in-house automated assembly capability.

The study was undertaken to determine how automation would reduce fabrication costs or increase array reliability, or both, particularly at greatly increased assembly rates than heretofore. Additionally, a secondary subject studied was automated handling of state of the art thin (50 micron) cells to minimize attrition from human handling.

The study is reported in the Technical Discussion section of this report, divided into three major sub-sections. The first section describes in detail the present in-house automated assembly capability and its potential for increased through-put rates, together with methods for accomplishing the increases. The second sub-section describes the assumptions, limitations and calculations concerning a 50 kw photovoltaic blanket, the resulting manufacturing requirements, production schedules and a comparison of the capacity of the existing in-house capability to meet the requirements of a 50 kw - eight month assembly. Each of three cell types is considered as an alternative.

This section also reports costs for each of the three alternative cell blankets if manufactured using the existing capability, and cost reductions which would result from two stages of increased automation.

In the third sub-section are cost-benefit analyses in the form of tables showing cost-saving and future investment necessary at each manufacturing step, as well as other tables showing attributes as related to costs.

One surprise during the study was that the existing automation capability could meet the 50 kw production requirements, albeit on a three-shift basis, illustrating a previously unrecognized attribute of automation: greater range of through-put rates than manual operations within a fixed floor space.

The approach used was to consider the fabrication of a 50 kw photovoltaic blanket in a period of eight months as a measure of through-put of existing and projected automated assembly techniques and their potential cost effectiveness.

Three solar cells were specified, each to be considered for assembling in an array blanket: 2 x 4 x .02 cm weldable wrap-around contacts, 2 x 2 x .005 cm weldable standard bar contacts and 3 x 3 x .005 cm weldable standard bar contact. Although the existing automated machines can be used either for welding or for re-flow soldering, this study concentrated on welding.

#### Work Plan

The study was divided into four (4) tasks as follows:

FIRST TASK MANUFACTURING REQUIREMENTS

- Define scope and assumptions
- Draw flow plans
- Estimate required manufacturing rates
- Estimate equipment and facilities.

SECOND TASK PRODUCTION CAPABILITIES

- Describe and rationalize existing equipment
- Specify flow plans
- Quantify potential for further automation

THIRD TASK PROCESS EVALUATION

- Correlate requirements and capabilities
- Identify improvements and innovations

FOURTH TASK COST - TRADE STUDY

- Define and graph cost benefits
- Estimate market for investment attraction

A detailed work plan was submitted to JPL on September, 1978, "Initial Program Plan."

Schedule

The program schedule is displayed in Figure 2.1-1. The schedule changes shown were made during the month of October when JPL directed that the planned fabrication of test coupons be deleted and the effort be directed instead to more detailed study. The re-distribution of effort was reflected in the changes of the program schedule.

STUDY OF AUTOMATED MODULE FABRICATION FOR  
LIGHTWEIGHT- SOLAR BLANKET UTILIZATION JPL 955205

L = LABOR  
M = MATERIAL/SUBCONTRACT  
O = ODC

NO.	TYPE	SUB TASK DESCRIPTION	1978					1979					
			AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1	L	PLANNING			↔								
2	L	MANUFACTURING REQUIREMENTS			↔	X	↔						
3	L	PRODUCTION CAPABILITIES			↔	X	↔						
4	L	PROCESS EVALUATION					↔	↔	↔				
5	L	COST-TRADE STUDY							X	↔	X	↔	
6	L	FINAL REPORT								↔	↔	↔	
7	L	ORAL BRIEFINGS							▲				
8	L	MONTHLY REPORTS							▲	▲	▲	▲	▲

### 3.0 TECHNICAL DISCUSSION

#### 3.1 The Automated Solar Blanket Process Concepts

TRW has, for some time, been guided by the realization that repetitious solar array assembly lends itself to automation, which thus reduces both assembly time and manufacturing cost, and results in a more uniform product. During this time TRW has learned that, even though large volume production activity requires a progressively more advanced level of automated production, automation of every operation is not the most cost-effective approach.

Several factors enter into selecting the level of automation leading to minimum cost at maximum productivity. TRW must consider equipment cost, degree of standardization, schedule, facilities, components to be assembled, and what impact the proposed automation might have on long-term reliability.

TRW has considered all of these factors during this study, and the resulting automated blanket assembly process is described below. Each process step is discussed at three levels: "Present System", "Near-Term" and "Future Optimized Automation". "Present System" describes the process step as it is done today. "Near-Term" describes what cost-effective process changes TRW foresees should reduce labor cost and improve quality in

the next 18 months. "Future Optimized Automation" describes what cost-effective process TRW foresees should further reduce labor cost and improve quality, but would take longer and require larger capital investment; this time-period is from 24 to 60 months.

Another view of these three levels of automation is to use the 50 kw-eight months assembly as a measuring tool. Using the "Present Capability" such a project would require two full shifts and a partial crew on a third shift, a situation in which any serious production stoppage practically guarantees schedule slippage. "Near-Term" automation would reduce the shift requirement to one full shift, a second partial shift and machine maintenance on third shift, a situation which permits management more flexibility in correcting serious production stoppages, therefore less likelihood of schedule slippage. "Future Optimized Automation" further reduces the shift requirements to one full shift, with machine maintenance on second shift, a situation which permits management the optimum flexibility in meeting delivery schedules.

#### Array Assembly Concepts

There are at least two array assembly concepts which could be used. One scheme has the interconnecting metal laminated into the polyimide substrate, with holes in the substrate wherever a weld connection is to be made, and is optimized for wrap-around contact cells. In this concept the glassed cells are placed backside-up on an alignment fixture; the polyimide substrate is carefully positioned on top of them and the welds are made through the holes. This concept has been

developed by Lockheed Missiles and Space Company for NASA-Marshall. All electrical connections are made while the component parts are in one fixture. The blanket panel would be fed through in 18 inch increments, so that an entire 30 inch x 12 feet panel would be assembled. The existing automated facilities are designed to function either with this scheme or the one that follows.

The other concept has the cell strings assembled with interconnectors separately from the substrate, and uses thin bondline adhesive to fasten the cell strings to the substrate. It is believed that this scheme results in a more producible, better-performing and more reliable array. It does this because:

- Cell location and spacing during fabrication are independent of dimensional instabilities of the polyimide substrate material, thereby eliminating serious positioning difficulties;
- The cells are provided with more effective heat-sinking to the substrate via the adhesive;
- The weld joint is not required to bear the stress of mechanically holding the cell on the substrate.

This concept is the one which will be addressed throughout the remainder of this report and described in greater detail.

#### The Process

The automated solar blanket fabrication process is divided into several subsections which are arranged in the general order of manufacturing flow:

- Interconnector welding to single cells.
- Cover glass installation.
- Module-to-substrate bonding.
- Module assembly.
- Panel inspection and testing.

See Figure 3.2.1.4-3 for Process Flow Chart.

Each of these processes will be discussed in detail below, identifying the present, near-term, and future processes.

### **3.1.1 Interconnector Welding**

For standard bar contact cells, the first manufacturing step is to weld interconnectors to the front contact because this connection-point will subsequently be covered with glass.

For the wrap-around contact cells, the application of the coverglass is the first step, described in Section 3.1.3.

#### **3.1.1.1 Present Process**

The present manufacturing step is mechanized, but not yet automated.

The operator removes cells from their styrofoam shipping container and places them face up in a specially-designed welding fixture. When the fixture is fully-loaded, a spring-clip hold-down is set in place. The fixture is then placed in a machine which cuts interconnectors from the feeder strip and places each interconnect in its proper location, with one end positioned properly on the cell. The operator removes the fixture from the machine, inspects it for proper alignment

of all interconnects, and places the fixture in the mechanized welder. The welder automatically performs one weld on each interconnector. Special circuitry monitors each weld pulse for a time integrated current signal; should the parameter exceed the preset limits, the machine shuts down and directs the operator to clean the weld electrodes. Visual inspection of a completed weld joint is difficult because the weld is obscured by the interconnect. At this operating station, an operator is in constant attendance.

When welds are completed, the operator removes the fixture, removes the hold-down clips and removes the cells, examining them briefly for general appearance and interconnect joint appearance. The operator then places the welded sub-assemblies in trays for the next step, the Quality Control Inspection.

The station described can process 5,000 welds per shift. As a general rule, there should be one weld joint per running centimeter on the top surface edge. This gives two joints for the 2 x 2 cm cell and three for the 3 x 3 cm cell. In that case, the station described above can process 2,500 cells 2 x 2 cm in size or 1,677 cells 3 x 3cm in size per shift. Soldering of interconnectors is also accomplished in a similar manner.

At specified intervals, random sample cells are subjected to destructive pull tests to verify the strength of the welds and the control on the machines.

### 3.1.1.2 Near-Term Improvements

The near-term process improvement would include:

- Work-station layout improvements and assembly fixture improvements as internally recommended by TRW Industrial Engineering Department. They estimated the reduction in lost motion by operators will reduce labor cost at this station by 40%.

### 3.1.1.3 Future Optimized Automation

- Cells would be received from suppliers in standardized carriers which provide a means for ready transfer to 500-cell magazines.
- For the welding operation, the cells are automatically removed from 500-cell magazines and positioned on a rotary indexing table with fixturing at each position of the table. A pick-and-place mechanism would constitute the first position. The second position would cut interconnectors from a supply roll and place them in precise alignment on each cell contact. In the third position, the welding of the first interconnector-to-cell joint would be performed. Subsequent stations would weld the second joint, then the third joint and so on; utilizing one welder per station as required by cell design. Each station would contain a weld-monitor with the necessary logic and connections to the table so as to

route a cell with an out-of-tolerance weld into a special cell tray. The weld stations would also contain the necessary electrode-cleaning functions presently incorporated in the X-Y module welding table. The next position would be an automated optical inspection station which inspects for cell cracking, interconnector alignment and other such points, coupled with the necessary logic circuitry to stop the table if rejects exceed a preset limit. The final station provides for removing the cell assembly from the indexing table and placing it either in a magazine for the glassing machine or in the reject receiving tray mentioned earlier. The labor reduction associated with this machine is projected at 90% from current values. Machine output target would need to be greater than 7,200 cells per shift at a yield greater than 99.9% on 50 micron cells.

### 3.1.2 Inspection: Interconnect and Cells

One inspector can perform microscopic inspection on 4,000 weld joints per shift. 100% inspection is standard procedure for actual space flight cells; in addition, any undetected shipping damage or other such problems can be intercepted at this point.

#### 3.1.2.2 Near-Term Improvement

Reduce inspection by using statistical sampling plans as applicable. TRW Quality Assurance Department judges that there is a high probability that a reduction from 100% inspection to a statistical sampling plan by batches or fabrication lots could be implemented during such a large and sustained fabrication program. Detailed procedures would be derived from the results of initial 100% inspection results.

### 3.1.2.2 Future Optimized Automation

Automatic inspection incorporated in preceding step to serve as process control as well as inspection.

### 3.1.3 Cover Glass Installation

For the 2 x 4 cm wrap-around contact cells, this would be the first manufacturing step. For the 2 x 2 cm and 3 x 3 cm cells with standard contacts, it would be the second major step. The automated machine described below will handle any of these configurations at the same manufacturing rate; so the description in this section deals with "cells" as a general term.

#### 3.1.3.1 Present Process

In order to feed the various components into the machine, it is necessary to have them loaded into three special carriers, called "magazines". The first magazine holds 500 individual coverglasses, the second holds the cells or cell sub-assemblies, and the third holds the cell glassing fixtures. Presently, each of these three magazines is hand-loaded.

The machine has many proprietary details, but the general sequence of machine operation is as follows: A glassing fixture is extracted from its magazine and positioned in a fixed orientation upon an indexing conveyor belt, then the belt advances one step. A cell sub-assembly is picked from its magazine and positioned properly on the glassing fixture. The belt advances another step and the silicone adhesive is

dispensed upon the cell in a measured amount. The belt advances another step and a coverglass is picked from its magazine and positioned on the cell in the fixture. The fixture is designed to position the coverglass with respect to the cell, so that the coverglass will overhang the cell on all four sides, thereby providing the most desirable radiation shielding. The belt advances one more step, the loaded fixture is pushed from the indexing belt on to a slow moving belt whose speed and length allow sufficient time for adhesive to spread to the limits of the interfacial area, before entering a pre-curing oven. The oven temperature and length provide an initial stage cure for the adhesive. At the exit from the oven, sufficient belt length is provided to allow the fixture and sub-assembly to cool before removal from the belt. The operator separates the glassed cell sub-assembly from the fixture. The fixtures are cleaned and freed of adhesive over-run and returned to the feed magazine. The cell assemblies are set into trays for the final adhesive cure cycle. The glassing machine operates at a rate of 3,600 cells per shift, requiring several operators. By adding a fixture-cleaning machine and fixture-removal and separation station to the glassing machine, fewer operators will be required. Later it is projected that both solar cells and coverglasses will be received from the vendors already loaded into containers which match the magazines for roll-transfer, again reducing labor cost.

Cleaning the adhesive over-run from the cell sub-assemblies is a hand operation, requiring repeated inspecting and cleaning. This operation is slow.

This step is also the point where misaligned cover-glasses are removed and cells cleaned up for re-work.

### 3.1.3.2 Near-Term Improvement

- The solar cell and coverglass magazines are presently loaded by hand. A hand-fed-semi-automatic machine has recently been placed in operation which simplifies this procedure, is more productive and reduces placement errors and component breakage. Altogether, labor content of this sub-routine will be reduced by about 60% from present value.
- A shortcoming of the automated glassing operation is in the lack of complete control of the adhesive viscosity used for bonding the cell to the coverglass. Too little adhesive results in incomplete bonding of the glass-to-cell interface producing voids; too much adhesive results in local adhesive spill-over, bonding the cell stack to its holding fixture, resulting in excessive labor in clean-up. Even though accurate dispensing equipment is employed, the adhesive has a short pot-life (less than one hour) during which its viscosity is constantly increasing. After considering several methods, the most cost-effective approach is to enclose the syringes in a small refrigeration chamber on the machine, since low temperature retards viscosity changes.
- In order to promote separation of cell stacks from the holding fixtures, the fixtures would be coated with a non-removable mold release such as Teflon. In past years, these coatings have been used and found unsatisfactory; lately, improved coatings have proved

to be satisfactory in other applications and are very promising for this application. Evaluation will be undertaken.

- A simple cell-stack holding fixture should be designed as a production aid for the removal of spilled adhesive. This, plus the adhesive controls on the glassing machine, are estimated to reduce labor by about 60% from current rates.

These short-term changes would reduce over-all labor by about 25% of present value.

### 3.1.3.3 Future Optimized Automation

- The logic system controlling the automatic glassing machine can be modified to increase the throughput rate by 20%.
- In order to glass thin cells, a weight must be added to the cell stack so that a curved cell is flattened to mate with the glass during adhesive cure. A spare position on the existing glassing machine could accommodate a weight-adding mechanism which would meet this need.
- An automated mechanism is being designed and will be built to remove the cell-stack and fixture from the conveyor belt, remove the cell stack from the fixture and place it in a 500 slot magazine. Meanwhile the fixtures will be cleaned and re-stacked on their loaders.
- The final, thorough cure of the silicone adhesive requires a 90-minute oven cure at 100°C. The curing oven may be of a conveyorized type when 500 cell magazines are used.

These advancements would reduce labor by about 90% from present values.

- An automatic cleaning machine could be built which would remove cell stacks from their magazine, place them on a conveyor, clean three surfaces, turn them over and clean the remaining three surfaces, then using an automated scanner, inspect the cells and place the accepted units into a magazine, while placing rejects into trays for re-work. Such a machine would reduce labor cost by about 90% from present levels.

However, a statistical and quality analysis should be performed to determine whether the machine described is indeed justified.

#### 3.1.3.4 Inspection After Glassing, and Cell Matching

Inspectors using stereomicroscopes and optical comparators presently inspect 1,000 cell assemblies per shift, per operator. Cells are inspected for cracked or chipped glass, adhesive voids or bubbles, cracked or chipped cells, and glass-to-cell alignment.

##### Near Term

No plans.

##### Future Optimized Automation

A transfer machine which removes cells from a magazine, inspects them as above and sorts them by optical character recognition of output class into other magazines. This step could be integrated into the automatic cleaning machine.

### 3.1.4 Module Assembly

In order to maximize power output from the array, cells are matched by their current output at a fixed voltage. Cells are marked by the vendor in current range groups per instructions from the array manufacturer. The assembly inspectors do the sorting described in step 3.1.3.4 since they are handling each cell prior to cell matching; they merely place the accepted cell assembly in an appropriately marked tray after inspection.

#### 3.1.4.1 Present Process

Modules are assembled in a precision fixture which locates each cell, maintaining proper cell spacing. The cells are glass-side-down in the fixture, and placed by cell grade. In certain assembly schemes, interconnector strings are put in after the cells are in place; the fixture can provide alignment for them, either parallel or series or both.

The loaded fixture is positioned over locating pins on a numerically-controlled X-Y table of an automated welding machine. The position of each weld has been programmed by N. C. tape, so the machine is capable of producing all welds automatically and unattended. More features of the machine will be discussed later in this section. In the case of the 2 x 4 cm wrap-around cells, all interconnect joints are welded at this step.

As was discussed in Section 3.1, this machine can also accommodate the optional laminated Kapton blanket with internal interconnects with wrap-around contact cells. Alignment holes in the blanket edges would be used with pins on the fixture edges to align weld points with the cells.

For standard contact cells, the previously attached interconnectors of one cell are oriented to rest on the back contact of the next cell in a series string. Parallel interconnect strings are added last, in cases where parallel arrangements are wanted.

For either type of cell, after welding is completed, the unwanted joining strips between interconnectors are removed while the module is still in the fixture.

In order for the welding machine to operate automatically, weld monitoring circuitry is built in. For weld-pulses detected below the pre-set limit, the machine will move automatically to an electrode cleaning station, scrub the electrodes, then return to the last weld joint made re-strike it and continue, if the proper weld is detected. Optionally, the monitoring circuitry can be set to provide a printed record of each weld if required. Upon completion of the last weld, the machine stops and the fixture is removed from the welding machine by an operator and another loaded fixture is positioned in its place. The fixture containing the welded module is then further processed by removing the aforementioned interconnect joining strips. Thereafter, the module

is submitted for Quality Assurance Inspection. The module is left in the fixture during inspection so that any rewelds can be performed without additional cell handling.

The size of the fixture for this study contract was determined to be about 15 x 36 inches. This size is easily accommodated on the machines. Engineering studies concluded that the number of cells in each module would be as follows:

- For 2 x 4 x 0.02 cm wrap-around cells, the four modules necessary for a 15 inch x 12 foot half-panel would have two modules of 18 x 23 (414) cells and two of 18 x 22 (396) cells.
- For the 2 x 2 x 0.005 cm cells, there would be two modules of 18 x 45 (810) cells and two of 18 x 44 (792) cells.
- For the 3 x 3 x 0.005 cm cells, there would be three modules of 12 x 30 (360) cells and one of 12 x 29 (348) cells.

The welder is capable of 6,300 welds per shift. For the 2 x 4 x 0.02 cm cell with wrap-around contacts, eight welds must be made on each cell: four for the positive contact and four for the negative contact, or 786 cells per shift per day. These rates are based on seven hours of operating time per shift, so as to consider loading/unloading time and other normal interruptions. It probably would be feasible to complete two modules per shift per day - 810 cells. For the thin standard contact cells, two of the welds are already completed, so 3,150 cells can be welded per shift per day. As above, at a slightly increased effort, four modules per day per shift could be done - 3,204

cells. In a like manner, for the 3 x 3 x 0.005 cm cells, three welds are to be made per cell, so 2,100 cells can be done. As before, six modules, 2,142 cells, could probably be done per shift.

#### 3.1.4.2 Near-Term Improvements

Add a second X-Y table during 1979, and relocate workstations preceding and following the X-Y automated welder. Labor saving about 5%.

#### 3.1.4.3 Future Optimized Automation

Add a third X-Y automated welding table. Design and build an automated pick-and-place machine which can pick cells from any of several magazines and lay the cells in strings on the module assembly fixture. Labor reduction, about 50% of current value.

#### 3.1.5 Inspection - Module Welding

##### 3.1.5.1 Present Method

The welded module is inspected, using a ten-power stereomicroscope, for weld electrode-imprints while the module is still in the fixture, so rewelding can be performed readily, and resubmitted for reinspection. Rates on this operation are presently not available.

##### 3.1.5.2 Near-Term Improvement

No change.

### 3.1.5.3 Future Optimized Automation

Study and select one or more of the non-destructive testing systems (see section 3.1.9) to determine module weld integrity, alignment of cells and the like. Use of such devices was estimated to reduce inspection costs by about 70% from current value.

### 3.1.6 Bonding of Module to Substrate

#### 3.1.6.1 Present Method

The accepted module is removed from the fixture with a vacuum pickup mechanism and transferred to a layout called a "Road Map" to check cell sequence and to aid the module selection process during the bonding operation. A second vacuum fixture transfers the module to an automated adhesive dispenser. This automated machine is currently in operation, configured for a 10 inch x 40 inch module size. The dispenser is capable of dispensing a measured amount of adhesive on a 2 x 2 cm cell, or two dots of adhesive on a 2 x 4 cm or 3 x 3 cm cell. Based on the current operating rate of the machine, it is projected that it can apply adhesive to any of the aforementioned modules in less than seven minutes per module. After the adhesive is applied, the vacuum holding fixture is removed from the dispensing machine, turned over and the module is positioned on the Kapton substrate on the lay-up table, the vacuum is released and the vacuum fixture removed. Once the cells are in location, hold-down weights are added to the module, one weight for each cell. These weights are in linear strips

for ease of handling, and are designed to apply a specific force to each cell to ensure proper adhesive spreading and bond-line thickness during cure.

After curing, the subject module is interconnected with its next neighbor and is cleaned.

#### 3.1.6.2 Near-Term Improvements and Future Automation

Widen the adhesive dispenser machine base to accommodate this module size.

#### 3.1.7 Test

##### 3.1.7.1 Present Method

The completed panel is transported to the test facility where it is exposed to a Xenon flash which simulates AM0 sunlight. This is the Large Area Pulsed Solar Simulator. The 1.7 millisecond flash is sufficient for the attendant circuitry to obtain all necessary panel performance information, which is then printed out by the equipment. It is still possible at this stage to rework the panel, if necessary.

##### 3.1.7.2 Near-Term Improvements and Future Automation

No improvements in this operation seem necessary at this time.

#### 3.1.8 Inspect

### 3.1.8.1 Present Process

After the panel has passed the performance test, the final inspection is performed before storage or shipment to insure all parameters are within specified limits.

### 3.1.8.2 Near-Term and Future Optimized Automation

No specific improvements in this operation seem necessary at this time to meet future requirements.

### 3.1.9 Automated Inspection Equipment, a Survey

A preliminary survey was conducted on commercially available automated inspection equipment. The purpose of this survey was twofold. First, to determine whether the candidate equipment could accurately detect defects at the various stages of solar cell assembly and second, to correlate these findings with manufacturing requirements of the 50 kw/eight months blanket. Two candidate systems are: The thermal imaging system and the optical line-scanning system.

- Thermal Imaging System

This system quantitatively evaluates the temperature differential of a solar array by producing infrared thermograms while the array is under load. It is postulated that a large  $\Delta t$  could indicate a sub-standard weld joint due to the excess resistance. Correlation between varying  $\Delta t$  and its relationship to weld joint integrity would need study.

- Line Scanning System

This electro-optical system provides applications in pattern recognition, facsimile, non-contact measurement, size and position monitoring, process control, inspection, and surveillance. When coupled with a programmable processor, the system is capable of characterizing the inspection functions and providing pass/fail decision capability.

### 3.2 The Solar Blanket Automated Production Concept

This section describes the several optional array blankets which would be built using the manufacturing process described in Section 3.1.

First the design criteria is described; the calculations to estimate the blanket size and quantity requirements are shown. The power-to-mass ratios are shown, preceded by the calculations used to establish them.

The production costs for each of the optional blankets if assembled in the present facility are listed; they are shown for assembling by the "Near-Term Improved" process; last they are shown for the "Future Optimized Automated" process. The investment costs and resulting cost savings are shown for each of the improvements.

#### 3.2.1 Description of Solar Array Blankets

This section describes the assembled blankets and their sizing based on the power, weight and component requirements and options.

##### 3.2.1.1 Power and Weight Requirements

The array power requirement is 50 kw. An estimate for the watts-per-kilogram rating was made with several assumptions concerning packing factors, interconnectors, and other general design considerations, for the three types of assemblies which are identified as:

Assembly #1 2 x 4 x 0.02 cm wrap-around cells.

Assembly #2A 2 x 2 x 0.005 cm standard contact cells.

Assembly #2B 3 x 3 x 0.005 cm standard contact cells.

Packing Factor

Packing factors are decimal fractions denoting the ratio of active cell area to total array area. Certain simplifying assumptions were made, however unrealistic they may be:

- There are no inactive areas in the blanket for integral electronics, or wiring harnesses.
- There are only very narrow borders on the substrate for attachment to support structure, about 1/4 to 3/4 inches.
- All solar cells, interconnectors and coverglasses are the exact design dimensions.
- All inter-cell inactive areas (gaps) are the exact design dimensions.

With these simplifications, it can be seen that the packing factor can be calculated relatively easily. Cell spacing for these cells is based upon several considerations:

- Existing guidelines for thermally-induced displacements in solar array configuration using 50 micron Kapton substrate.
- Production accuracy in placing cells adjacent to one another.
- Experience in avoiding inter-cell and intra-cell shorting in space applications.
- Coverglass which slightly overhangs the cell it covers.

Two values were selected:

- 0.051 cm (0.020") in the series-connected direction.
- 0.051 cm (0.020") in the parallel-connected direction including stiffeners as described in Section 3.2.1.3.

These values are valid for all three types of cells. Packing factor calculations:

For Assembly #1 - .93 (See Section 3.2.1.3)

For Assembly #2A - .92 (See Section 3.2.1.3)

For Assembly #2B - .922 (See Section 3.2.1.3)

#### Interconnectors

Interconnectors were assumed to be simple rectangles of reasonable dimensions to meet electrical conductivity requirements. The dimensions approximate an equivalent actual in-plane stress relief type interconnector.

#### Cell Power Ratings, Temperature Considerations

All cells are 11% efficient at 28<sup>o</sup>C when illuminated at AM0 conditions.

A 2 x 4 cm 11% cell would produce 119 mW at 28<sup>o</sup>C. Called-out array operating conditions are at 55<sup>o</sup>C in earth orbit. Cell power was de-rated 0.5% per degree Celsius.

De-rating for temperature:

Sample calculations: For the 2 x 4 x .02 cm wrap-around cell

$$119[1.0(55 - 28 \times 0.005)] = 103 \text{ mW at } 55^{\circ}\text{C}$$

Installation on an array blanket will reduce the power by 2%. This percentage represents worst-case power losses from coverglass installation, interconnection losses and cell mismatches reducing the performance to:

$$101 \text{ mW at } 55^{\circ}\text{C}$$

TABLE 3.2.1-1

Mass Properties Calculation for Single Solar Cell - Array Assembly #1  
 Excluding Support Structure and Electrical Bus  
 Cell Size 2x4x0.02 cm. Wrap-around Contacts

ITEM	DENSITY (g/cm <sup>3</sup> )	NOMINAL SIZE (cm)	NOMINAL MASS (mg/cell)	FRACTIONAL MASS (Percent)	UNCERTAINTY <sup>(1)</sup> (mg/cell)
Microsheet Coverglass	2.51	2.02x4.02x0.0075	152.9	21.2	51.2
Cover Adhesive	1.08	2.02x4.02x0.0025	22.0	3.0	22.0
Solar Cell	2.60 <sup>(2)</sup>	2.0 x 4.0 x 0.020	416.0	57.6	52.0
Inter- Connectors (4 per cell)	9.3 <sup>(2)</sup>	0.26x.775 x .005	37.5	5.2	--
Substrate <sup>(3)</sup> Adhesive	1.5	2.0 x 4.0 x 0.0025	32.2	4.5	31
Polyimide <sup>(3)</sup> Substrate	1.42	2.0 x 4.0 x 0.0050	61.1	8.5	--
TOTAL			721.7	100	156.2

## FOOTNOTES:

- (1) Uncertainty based on 25-micron variation in item thickness
- (2) Weighted average density for plated piece part.
- (3) Mass includes correction for 0.93 packing factor

TABLE 3.2.1-2  
 Mass Properties Calculation for Single Solar Cell - Array Assembly #2A  
 Excluding Support Structure and Electrical Bus  
 Cell Size 2x2x0.005 cm. Standard Contacts

ITEM	DENSITY (g/cm <sup>3</sup> )	NOMINAL SIZE (cm)	NOMINAL MASS (mg/cell)	FRACTIONAL MASS (Percent)	UNCERTAINTY <sup>(1)</sup> (mg/cell)
Microsheet Coverglass	2.51	2.02x2.02x0.0075	76.8	37.3	25.6
Cover Adhesive	1.08	2.02x2.02x0.0025	11	5.4	11
Solar Cell	2.60 <sup>(2)</sup>	2.0x2.0x0.0050	52	25.3	6.5
Inter-Connectors (2 per cell)	9.3 <sup>(2)</sup>	0.260x0.775x0.0050	18.7	9.1	--
Substrate <sup>(3)</sup> Adhesive	1.5	2.0x2.0x0.0025	61.3	7.9	15.8
Polyimide <sup>(3)</sup> Substrate	1.42	2.0x2.0x0.0050	30.9	15.0	--
TOTAL			205.7	100	58.9

FOOTNOTES:

- (1) Uncertainty based on 25-micron variation in item thickness.
- (2) Weighted average density for plated piece part.
- (3) Mass includes correction for 0.92 packing factor

TABLE 3.2.1-3

Mass Properties Calculation for Single Solar Cell - Array Assembly #2B  
Excluding Support Structure and Electrical Bus  
Cell Size 3x3x0.005 cm Standard Contacts

ITEM	DENSITY (g/cm <sup>3</sup> )	NOMINAL SIZE (cm)	NOMINAL MASS (mg/cell)	FRACTIONAL MASS (Percent)	UNCERTAINTY <sup>(1)</sup> (mg/cell)
Microsheet Coverglass	2.51	3.02x3.02x0.0075	171.7	38.4	57
Cover Adhesive	1.08	3.02x3.02x0.0025	24.6	5.5	24.6
Solar Cell	2.60 <sup>(2)</sup>	3.0x3.0x0.0050	117	26.1	14.6
Inter-Connectors (3 per cell)	9.3 <sup>(2)</sup>	0.260x.775x.005	28.1	6.3	--
Substrate <sup>(3)</sup>	1.5	3.0x3.0x0.0025	36.6	8.2	34.7
Polyimide <sup>(3)</sup> Substrate	1.42	3.0x3.0x0.0050	69.3	15.5	--
TOTAL			447.3	100	130.9

FOOTNOTES:

- (1) Uncertainty based on 25-micron variation in item thickness.
- (2) Weighted average density for plated piece part.
- (3) Mass includes correction for 0.922 packing factor.

thus:

For Assembly #1 - the  $2 \times 4 \times .02$  cm cell = 101 mW

For Assembly #2A - the  $2 \times 2 \times .005$  cm cell = 50.5 mW

For Assembly #2B - the  $3 \times 3 \times .005$  cm cell = 113.6 mW

Power-to-Mass ratio sample calculation:

$$\text{Assembly } \#1 \quad \frac{101 \text{ mW}}{721.7 \text{ mg}} \times 1000 = 140 \text{ W/kg}$$

The results of the computations are in tables 3.2.1-1, -2,-3, and -4; showing the mass property calculations for array Assembly #1, #2A, and #2B respectively. Table 3.2.1-4 compares the estimated power-to-mass ratios of the three assemblies, identifying array Assembly #2B as the most favorable.

TABLE 3.2.1-4

Estimated Power-to-Mass Ratios, Watts per Kilogram

ITEM	JPL Target Values	Estimated Nominal Values
Assembly #1	106	140
Assembly #2A 2 x 2 Cells	240	246
Assembly #2B 3 x 3 Cells	240	254

### 3.2.1.2 Component Description

Another facet in meeting the Manufacturing Requirements is the availability of essential materials in the make-up of the solar array blanket and the vendors capability in supplying these materials in an appropriate time frame. Efforts were made in this study to seek out any logistic problem on the essential ingredients: Solar cells, cover glass, adhesives, interconnectors, and substrates.

#### Solar Cells

Spectrolab, OCLI and Solarex were contacted and the availability of cells of these designs were discussed with them. Spectrolab and OCLI produce the 2 x 4 cm 200 micron thick cell with weldable wrap-around contacts, but only in laboratory quantities on special order in 1979.

All three produce the thin (50 micron) 2 x 2 cm cell, in laboratory quantities. Only Solarex expressed interest in the 3 x 3 cm thin cell. For this study, therefore, it must be assumed than required quantities of cells are on hand at the beginning of the assembly, and that there are no unresolved array assembly problems related to cell construction. Taking into account complexity factors, cell thickness and historical experience, the quantities required should be estimated at 5% more than the actual lay-down cell quantity. This 5% attrition is an extrapolation from the past experience on progressively thinner cells and progressively more automatic assembly.

#### Cover Glass

Coverglass, either ceria or silica, requires long lead times to obtain,

and there are significant yield losses for the intermediate processors in selecting the 75 micron-portions of the sheets manufactured by either Pilkington Ltd. or Corning Glass Works

Cutting the glass to size also generates significant yield losses, whether by Spectrolab or by OCLI-Santa Rosa or Pilkington. For these reasons, it is assumed that sufficient coverglass is on hand at the start of the eight-month period, and in the necessary quantities, which amounts to 7% more coverglass than the laid cell quantity (thinner glass has higher attrition for a given area). The coverglass is less costly than the cells, so fabrication procedures will minimize cell loss at the expense of the glass.

#### Adhesives

The adhesives used to fasten the coverglass to the cell and for fastening the cells to the polyimide (Kapton) substrate have limited shelf lives. It is assumed that a steady supply is received as needed.

#### Interconnects

The interconnector to be used must be flexible, fatigue-resistant and weldable. Silver-plated Invar is the material of choice. It is assumed that a suitable interconnector has been designed, fully tested in flight simulation, and fabricated in the necessary quantities equal to 107% of the laid cell quantity; again, fabrication and rework procedures favor the cell at the expense of the interconnector.

#### Substrate

The polyimide substrate, Dupont Kapton, is available in thicknesses from 6 to 125 micron. The 50 micron thickness is available in widths

to 60 inches and lengths to 5,000 feet; therefore, there are wide choices available for panel or module size. It is assumed that the Kapton needed is available and the panel (substrate) fabrication can be done without influencing the production schedule for cell lay down.

### 3.2.1.3 Module Blanket Sizing

#### Foldable Configuration

The panel design must be considered to the extent necessary to decide on cell quantity in a subsection. As a rough estimate, 50 kw at 11% efficiency, .95 packing factor, irradiated with AM0 sunlight results in a minimum area requirement of 354 square meters (3,807 square feet). (Actual packing factors and de-rating from Section 3.2.1 will increase this area.) Jet Propulsion Laboratory was asked for guidance on the selection of dimensional choices in this matter, and they recommended limiting one dimension to twelve (12) feet. In that case, a theoretical minimum length for the 50 kw array is 317 feet.

The 12 foot limit fits into certain existing panel assembly fixturing, which is 50 inches wide and 13 feet long. The width of 30 inches is chosen as a convenient width for panel assembly. Larger fixturing is available as needed. The 13 foot fixture length is intended to be longer than the panels, to provide additional space at the ends of the longer dimensions for certain commonly occurring fabrication steps at panel ends.

After studying several proposed designs for future NASA solar array blankets, it was decided to locate a fold-line about every 15 inches in the long dimension of the panel; so, a subsection of the panel would be

15 inches by 12 feet. A unit panel would consist of a polyimide substrate about 30 inches wide and 12 feet long, containing two sub-panels.

Polyimide (Kapton) has physical properties which must be considered in the detailed dimensioning of the substrate. It is tough, and notch sensitive. For space applications, a joint must be of an overlapping type, to minimize those shortcomings.

In order to provide joining and folding space, a one-half inch fold line is provided at the middle of the 30-inch dimension, and one-half inch seam is provided at each edge. These edge seams are intended to overlap and form a hinge from one panel to the next, providing a 15-inch wide solar cell area separated by a one-half inch fold line, repeating along the long dimension of the array.

With the general dimensions of the panel defined, the detail can be calculated. A recent meeting (October 1978) and presentation at Lockheed Missile Space Systems demonstrated a panel system which is close enough to the requirements of this study to enable its use for this part of the study.

Those panels are about 30 inches wide and about 12 feet long. They are subdivided into four sub-panels, each about 15 inches wide by 6 feet long. Because of a need for stiffening the Kapton substrate in the 15-inch direction, stiffeners are run in that direction, so the

series strings of cells are laid between. One 15 inch by 6 foot panel is connected as a single series string, with the electrical current flowing in opposite directions in adjacent cell rows, for first order electromagnetic field cancellation.

To calculate how many cells can be fitted into the area, arbitrary maximum limits on the dimensions were assigned. The width shall be 30 inches and the length shall be 12 feet. Three borders of one-half inch interrupt the 30 inch dimension; one at each edge and one in the center. This leaves two times 14.25 inches of free panel width for cells.

In Section 3.2.1.1, cell spacing was discussed. To account for the width of the stiffeners, which are described only in generalized terms, additional 0.010 inches of spacing in the parallel-cell direction was arbitrarily chosen as representing the stiffener width, again reducing packing factors. It may be found later that fewer stiffeners are needed. The resulting parallel cell spacing is .020 inches (about 500 microns). These results lead to the tentative conclusion that a quarter panel, 15 inches x 6 feet, is a convenient unit for calculations, since it comprises a simple series string in the case of the 2 x 4 and 3 x 3 cells. For the 2 x 2 cells, it constitutes 2 series strings, which leads to possibly parallel-connecting a pair of cells and using the pair as if they were a 2 x 4 cm cell to form a series string.

A further refinement would be to parallel-connect cells in each 15" x 6' quarter panel so that two side-by-side quarter panels could have a simple connection between them at their inboard end and array cabling

can all be located under the outboard edges of the blanket. For the 2 x 4 cm cell, two side-by-side quarter panels would constitute 810 series connected parallel pairs developing 337 volts and 164 watts. For the 2 x 2 cm cell, it would be 801 series connected parallel quartets, developing 333 volts and 162 watts. For the 3 x 3 cm cell, it would be 714 series connected parallel pairs, developing 297 volts and 162 watts.

#### Roll-up Array Configuration

A roll-up blanket array configuration using the thin cells was to be considered. From the assumptions and dimensions chosen in the preceding section on the foldable blanket, only a minor change would be needed for the roll-up configuration. The half-inch fold line at 15 inches can be eliminated, thereby making a 30 inch by 12 foot panel, with half-inch seam lines along the 12 foot dimension. This leaves an area for solar cells which is 29 inches wide, a slightly more efficient use of area than for the foldable array blanket.

The resulting 30 inch by 12 foot panels would have double the power output of the half-panels described in the immediately preceding section, and double the number of cells:

- For 2 x 2 cm cells—6408 cells

Eight series strings of 801 cells each developing 333 volts and 324 watts requiring 155 panels, and the array being 381 feet long.

- For 3 x 3 cm cells—2856 cells, 8 series strings of 714 cells, developing 297 volts; the other parameters are the same as for the 2 x 2 cells.

### Module Size

A module with dimensions of 15 by 36 inches was chosen as compatible with either array and easily accommodated on current automated module assembly equipment. The 15 inch direction is the same as the subpanel dimension, the 36 inch dimension is one fourth of the 12 foot array dimension. Figure 3.2.1.3 shows a sketch of the panel concept.

### 3.2.1.4 Requirement of Array Blankets and Hypothetical Production Rates

The various JPL requirements for the two alternate array blankets, exclusive of major structural supporting and extending mechanisms, but including the various options, are as follows:

#### Solar Array Blanket Assembly #1

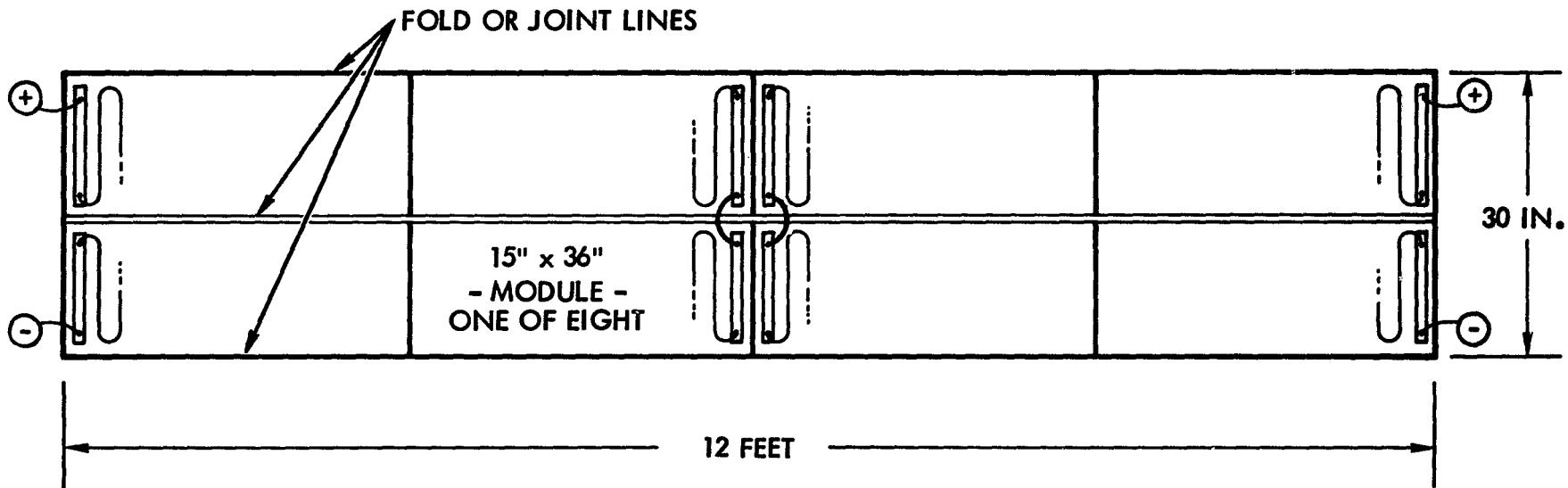
- 50 kw blanket operating at 55°C in earth orbit.
- Assembly time to not exceed eight months in the 1980 time frame.
- Use of a 200 micron thick 2 x 4 cm solar cell (11% efficient) with wrap-around welded contacts.
- 75 micrometer thick, 2 x 4 cm coverglass.
- 50 micrometer thick, Kapton polyimide substrate.
- High power-to-mass ratio (a goal of 106 w/kg). (See Table 3.2.1-4).
- Blanket module voltage from 200 volts dc to 400 voltsdc.
- Compatability with foldable array.

#### Solar Array Blanket Assembly #2 (Options A and B)

- 50 kw blanket operating at 55°C in earth orbit.
- Assembly time not to exceed eight months in the 1980 time frame.

STUDY OF AUTOMATED MODULE FABRICATION FOR  
LIGHTWEIGHT SOLAR BLANKET UTILIZATION

SKETCH OF PROPOSED SOLAR PANEL FOR BLANKET  
50 KW REQUIRES 155 PANELS



POWER:  $325 \pm 2$  WATTS

VOLTAGE:  $317 \pm 10$  VOLTS

- Use of 50 micron thick solar cells (11% efficient) with standard bar welded contacts, with two options:
  - OPTION A - 2 x 2 cm size (This is Assembly #2A).
  - OPTION B - 3 x 3 cm size (This is Assembly #2B).
- Coverglass:
  - OPTION ONE - 75 micrometer glass.
  - OPTION TWO - equivalent radiation protection (see comment, end of this sub-section).
- 50 micrometer thick Kapton polyimide substrate.
- High power-to-mass ratio (a goal of a 240 w/kg blanket).
- Blanket module voltage from 200 volts dc to 400 volts dc.
- Compatability with either:
  - OPTION ONE - foldable array
  - OPTION TWO - roll-up array

Comment on coverglass options:

As of this writing, no viable alternative covering materials have proved out as substitutes for glass as a covering, although many researchers have investigated alternatives. TRW has, for example, fabricated flexible blanket sample panels using a Kapton substrate and FEP Teflon as the cell covering. After simulated space testing, it was found that the FEP Teflon was degraded by ultraviolet and particle bombardment more quickly than was anticipated. (Rauschenbach, H. S., and Cannady, M. D., Final Report - Flexible FEP-Teflon Covered Solar Cell Module Development, October, 1976, NAS 3-16742.) The alternates do not deliver as high an end-of-life power rating. (Goldhammer, L. J., Improvement and Extension of Data from ATS-6 Radiation

Damage Experiment, Hughes Aircraft, March, 1979, NAS 5-24458). This automation study then concentrated on glass as a covering.

Hypothetical Production Rates

To arrive at the hypothetical production rates, the quantity of each of the components to be assembled has been calculated for the 50 kw requirement. These quantities are shown in Table 3.2.1.4-1.

These quantities were then used to generate a hypothetical manufacturing schedule to meet the eight-month assembly time requirement and is shown in Figure 3.2.1.4-2.

The assembly Flow Chart for this project is shown in Figure 3.2.1.4-3.

TABLE 3.2.1.4-1

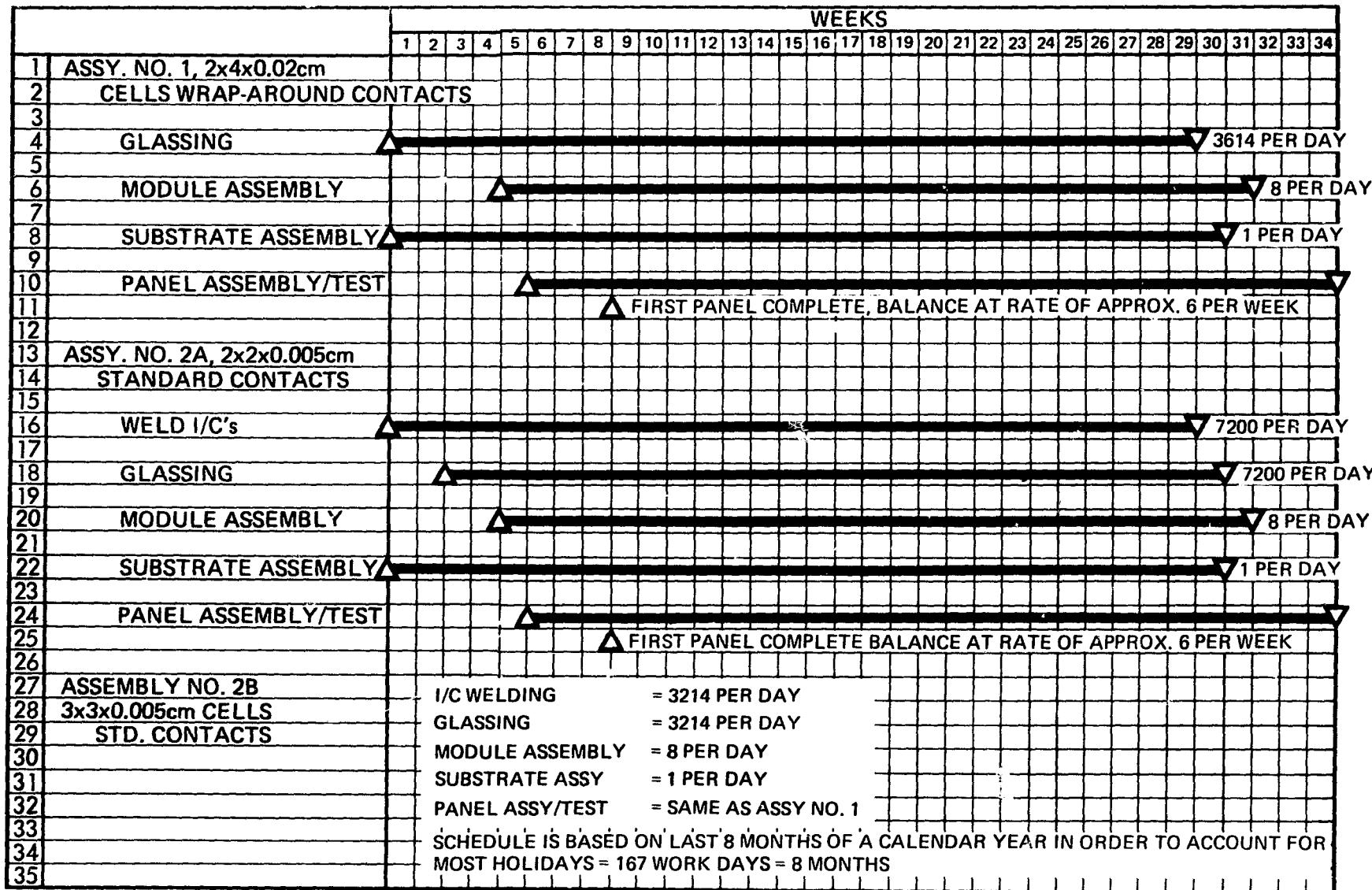
**TRW**  
DEFENSE AND SPACE SYSTEMS GROUP

MANUFACTURING REQUIREMENTS

## TABULATED SUMMARY

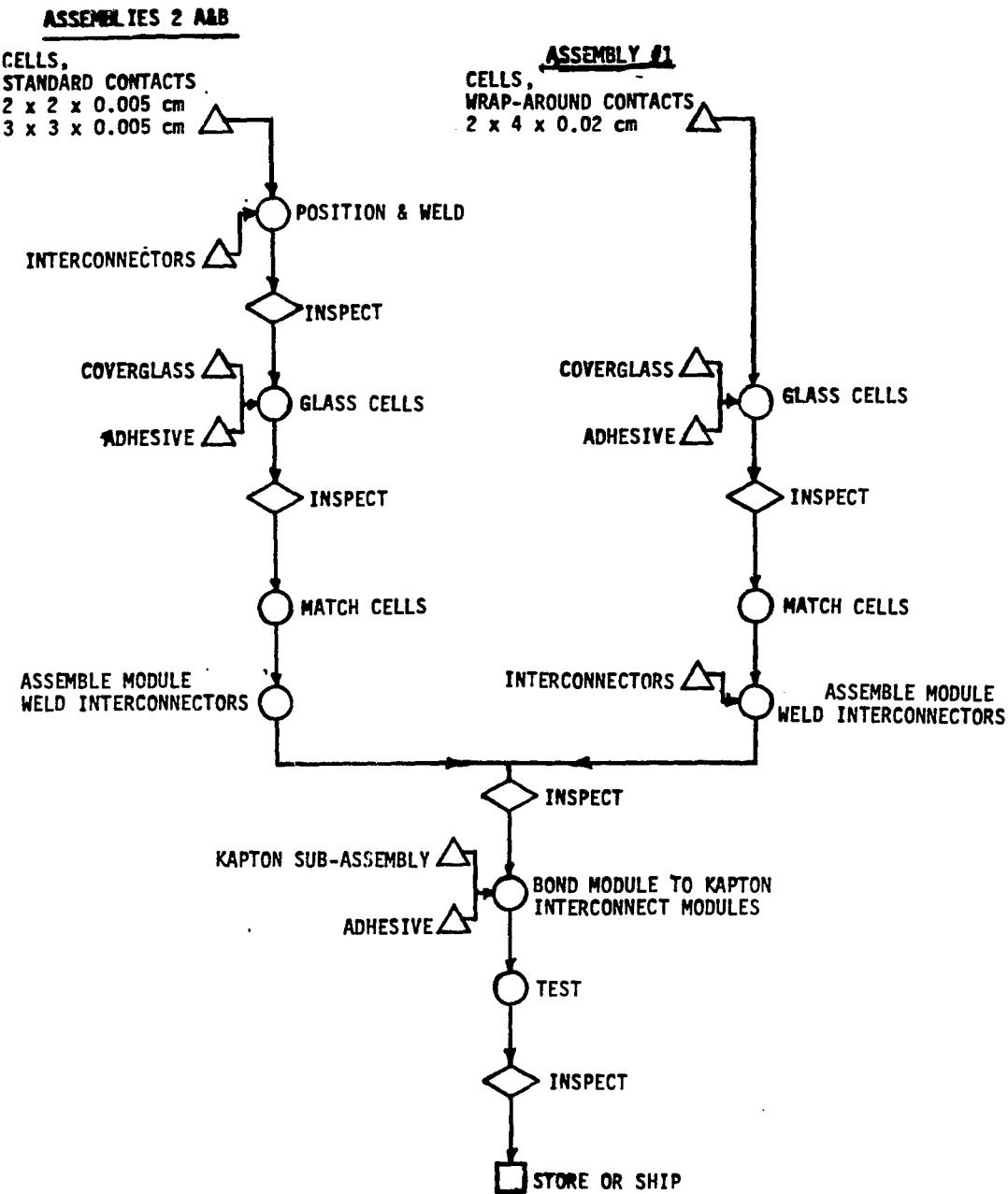
ITEM	CELL TYPE	2 x 4 x .02 cm WRAP-AROUND CONTACT	2 x 2 x .005 cm STD. CONTACT	3 x 3 x .005 cm STD. CONTACT
FINAL ARRAY QUANTITIES		499,000	994,00	443,000
CELL QUANTITIES NEEDED 105%		524,00	1,044,000	466,000
QUANTITIES OF COVERGLASSES 107%		534,000	1,064,000	475,000
QUANTITIES OF INTERCONNECTS 107%		2,136,000 4 PER CELL	2,128,000 2 PER CELL	1,398,000 3 PER CELL
NUMBER OF 30" x 12' PANELS IN ARRAY		154	155	155
CELLS PER PANEL		3,240	6,408	2,856
NUMBER & CELL-COUNT OF 15" x 36" MODULES PER PANEL		4 @ 18 x 23 cells 4 @ 18 x 22 cells	4 @ 18 x 45 cells 4 @ 18 x 44 cells	6 @ 12 x 30 cells 2 @ 12 x 29 cells
APPROXIMATE LENGTH OF 50-MICRON KAPTON REQUIRED (30" WIDTH)		1,900 ft.	1,900 ft.	1,900 ft.
APPROXIMATE BLANKET DIMENSIONS - FEET		12x379	12x381	12x381

HYPOTHETICAL MANUFACTURING SCHEDULE  
50 KW LIGHTWEIGHT SOLAR BLANKET  
AUTOMATED MODULE FABRICATION STUDY, JPL #955205



**FIGURE 3.2.1.4-2**

FIGURE 3.2.1.4-3  
FLOW CHART, ASSEMBLY PROCESS STEPS



### 3.2.2 Present In-House Manufacturing Capability - Rates and Costs

For this portion of the study, the production of the 50 kw solar blanket at the present TRW solar array manufacturing facility was established as baseline. The present TRW production sequence is shown schematically in Figure 3.2.2-1. The actual optimized utilization of the equipment at each of the process steps are discussed, followed with a tabulated summary in Table 3.2.2.-2.

#### 3.2.2.1 First Step - Position and Weld Interconnects

The 2 x 2 cm cells require two welds each, while the 3 x 3 cm cells require three welds each. Manufacturing requirements call for 7,200 of the 2 x 2 cm cells per day and 3,214 of the 3 x 3 cm cells per day. The 2 x 2 cm cells represent 14,400 welds per day, and the 3 x 3 cm cells represents 9,642 weld per day. The semi-automatic interconnect weld station can produce 5,000 welds per shift. In order to meet manufacturing requirement just discussed for the 2 x 2 cm cell, this station must be operated for three shifts.

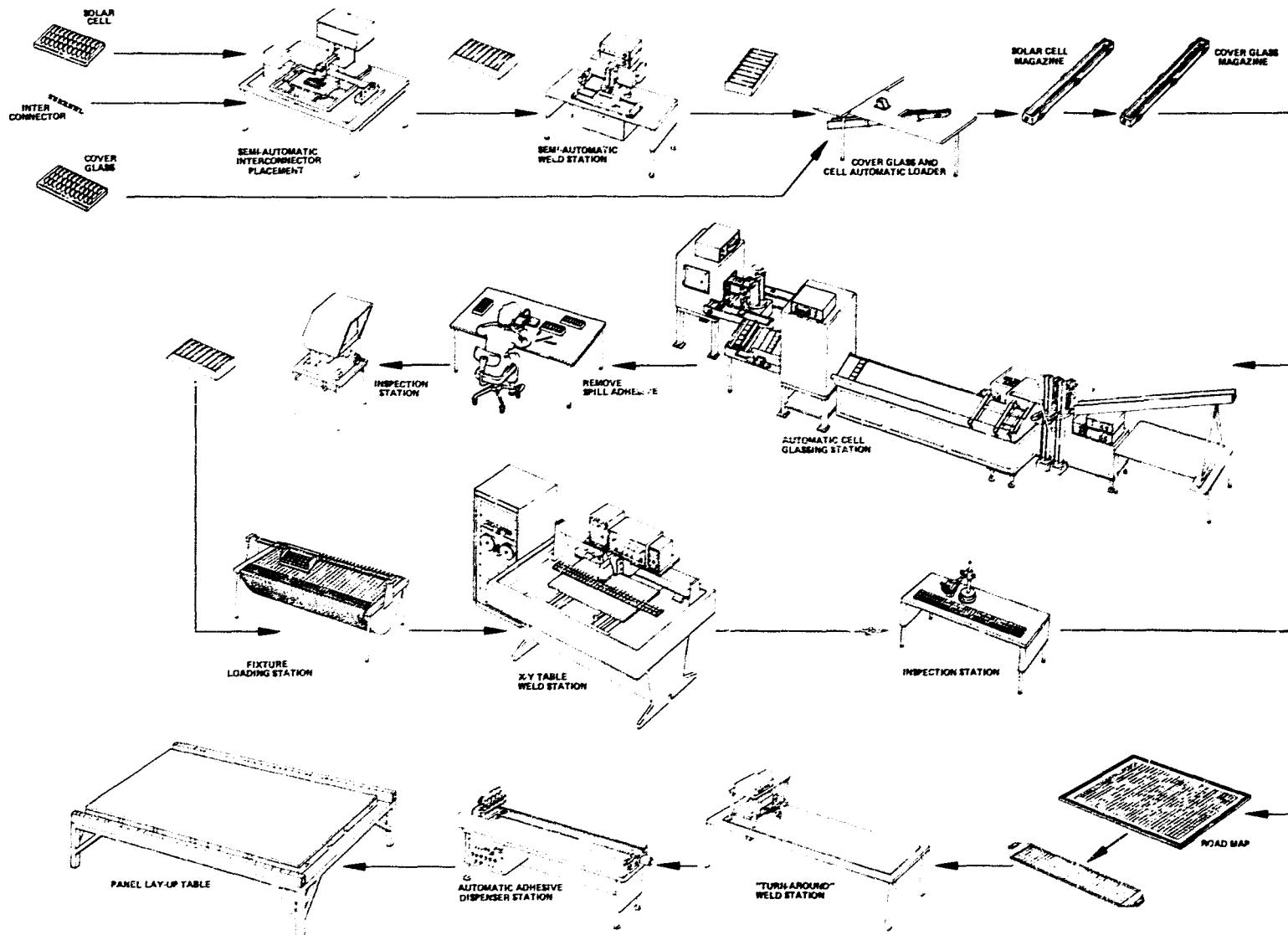
#### Second Step - Inspection

One inspector can inspect 4,000 welds per shift. For 2 x 2 cm cells, this requires two (2) inspectors on two shifts. For the 3 x 3 cm cells, it requires two inspectors on one shift and one on a second shift.

#### Third Step - Glassing

The present machine operates at the rate of 3,600 cells per shift. For the 2 x 4 cm wrap-around cells, 3,614 are required per day; so the present machine capability is sufficient. For the 2 x 2 cm cells, 7,200

FIGURE 3.2.2-1



## SEMI-AUTOMATED SOLAR ARRAY ASSEMBLY LINE

TABLE 3.2.2-2

MANUFACTURING REQUIREMENTS CORRELATED TO PRODUCTION CAPABILITIES  
NUMBERS REPRESENT DAILY QUANTITIES

	FIRST Position & Weld Inter-Connectors	SECOND Inspection	THIRD Glassing	FOURTH Inspection	FIFTH Match Cells	SIXTH Assemble Modules	SEVENTH Inspection	EIGHT Bond Module to Substrate	NINTH Test	TENTH Inspect
2 x 4 x .02 cm cell MFG. REQ.	-----	-----	3,614 cells	3,614 cells	3,614 cells	3,887 cells 31,104 welds	1,104 welds	9.6 modules	1.2 panels	1.2 panels
2 x 4 x .02 cm cell PROD. CAPAB.	-----	-----	3,600/shift	1,000/shift per person 4 Inspectors	Part of Fourth step	6,300/shift per machine	4,000/shift per person 8 Inspectors	10 modules	more than 2	more than 2
2 x 2 x .005 cm cell MFG. REQ.	7,200 cells 14,400 welds	7,200 cells 14,400 welds	7,200 cells	7,200 cells	7,200 cells	7,690 cells 15,380 welds	15,380 welds	9.6 modules	1.2 panels	1.2 panels
2 x 2 x .005 cm cell PROD. CAPAB.	5,000/shift Add second station	4,000/shift per person 4 Inspectors	3,600/shift (2 shifts)	1,000/shift per person 8 Inspectors	Part of Fourth step	6,300/shift per machine	4,000/shift per person	10 modules	more than 2	more than 2
3 x 3 x .005 cm cell MFG. REQ.	3,214 cells 9,642 welds	3,214 cells 9,642 welds	3,214 cells	3,214 cells	3,214 cells	3,428 cells 10,282 welds	10,282 welds	9.6 modules	1.2 panels	1.2 panels
3 x 3 x .005 cm cell PROD. CAPAB.	5,000/shift Add second station	4,000/shift per person 3 Inspectors	3,600/shift	1,000/shift per person	Part of Fourth step	6,300/shift per machine	4,000/shift per person	10 modules	more than 2	more than 2

are needed, so the present machine must be operated for two shifts. For the 3 x 3 cm cells, 3,214 are required, so the present machine is sufficient. The labor involved in cell stack cleaning is being reduced rapidly as of this writing and will continue to be reduced as automation progresses. It is, for the purposes of Table 3.2.2-2, considered part of the third step.

#### Fourth Step — Inspection After Glassing

An inspector presently can inspect 1,000 cell assemblies per shift per day. For 2 x 4 cm wrap-around cell, 3,614 cells must be inspected per day, requiring four inspectors, perhaps two on each of two shifts. For the 2 x 2 cm cell, 7,200 must be inspected, requiring four inspectors each on two shifts. For the 3 x 3 cm cells, 3,214 must be inspected, requiring two operators on each of two shifts.

#### Fifth Step — Match Cells

The above inspection rates include cell matching, which consists of sorting the accepted cell into a specific bin marked with a current output range.

#### Sixth Step — Module Assembly

The automated welder is capable of 6,300 welds per shift, per machine.

There are two machines at this station.

The 2 x 4 cm wrap-around cell requires a total of eight welds, four for the top contact and four for the bottom. All welds for this cell are performed on the automated welder at this manufacturing step. Manufacturing requires 1.2 panels per day, 3,888 cells per day; 31,104 welds requiring both machines operating on two shifts plus one operating on third shift.

For the 2 x 2 cm cells, 7,690 cells must be welded per day, requiring two

welds per cell, 15,380 welds. The two machines must be operated one shift, plus one machine on a second shift.

For the 3 x 3 cm cells, 3,428 cells must be welded, three welds per cell, 10,282 welds per day, which requires both machines operating on one shift.

#### Seventh Step — Inspection After Module Assembly

A rating of labor hours for this step is based on performing inspection using a stereomicroscope set at 10X magnification. This inspection can be performed at the rate of 4,000 welds per inspector per day. Therefore, in the case of the 2 x 4 wrap-around cells, 31,104 welds must be inspected per day, requiring eight (8) inspectors; preferably four on the first shift and four on the second shift. For the 2 x 2 cm cells 15,380 welds must be inspected, requiring four (4) inspectors. For the 3 x 3 cm cells, 10,282 welds must be inspected, requiring three (3) inspectors.

#### Eighth Step — Bond Module to Substrate

The machinery and techniques for this operation are mechanized well enough to allow the assembling of an entire panel (8 modules) in less than six (6) working hours, including module interconnections, regardless of cell size or substrate style (roll-up or foldable). It is possible to meet the 9.6 module daily requirement with one shift.

#### Ninth Step — Test

Testing facility and capacity are sufficient to handle and test the panels at the rate of six per week, as required, using the existing test facility (L.A.P.S.S.).

Tenth Step — Inspect

The final acceptance inspection is somewhat loosely defined at this point, since this study deals with a projected future array with unspecified test requirements. However, sufficient quantities of skilled inspectors and test facilities are available to perform whatever final inspection procedures may be required, based on past experience in building a qualified panels. The following table shows the manpower required for manual inspection:

TABLE 3.2.2-3

Inspection Function	Cell Size, cm	Mfg. Req. Quantity	No. of Inspectors Req'd - Present
Weld Inter-Connect	2 x 4 x .02	None	None
	2 x 2 x .005	7,200 cells 14,400 welds	4
	3 x 3 x .005	3,214 cells 9,642 welds	3
After Glassing	2 x 4 x .02	3,614 cells	4
	2 x 2 x .005	7,200 cells	8
	3 x 3 x .005	3,214 cells	4
After Module Assembly	2 x 4 x .02	31,104 welds	8
	2 x 2 x .005	15,380 welds	4
	3 x 3 x .005	10,282 welds	3
Final Acceptance	2 x 4 x .02	1.2 panels	> 2
	2 x 2 x .005	1.2 panels	> 2
	3 x 3 x .005	1.2 panels	> 2

### 3.2.2.2 Production Costs, Present System

In a study which projects a theoretical manufacturing facility of some kind, generally it is expected that projected costs will be reported in dollars.

In this study, it has been shown that the 50 kw blanket can be produced in TRW's present facility, and the projected costs are real instead of theoretical. We are then confronted with the possibility of revealing proprietary information. Therefore, all of the costs have been normalized, using the TOTAL COST of Assembly #1, at an assigned value of 100 as the basis and establishing ratios of that value for all other costs shown.

As an illustrative example, the purchase cost of solar cells (which in all three cases represent 105% of the laid-cell quantity) is 45.6 for Assembly #1, 90.9 for Assembly #2A, and 91.3 for Assembly #2B. Comparison of these figures shows that the thin cells cost twice as much as the wrap-around thicker cells, and cost almost as much as the total cost of Assembly #1. A comparative solar cell blanket TOTAL COST (purchased materials and assembly labor cost) is shown in Table 3.2.3A. The comparison of purchased materials and of assembly labor cost are respectively shown in Table 3.2.3B and 3.2.3C.

The rough order of magnitude of TOTAL COSTS is in the tens of millions of dollars, and the labor cost reductions effected by automation as shown in Sections 3.2.3 and 3.2.4 are in the millions of dollars.

## COMPARATIVE SOLAR CELL BLANKET COSTS

TABLE 3.2.2.2A

## TOTAL COST - PRESENT SYSTEM

Numbers normalized: TOTAL COST of Assembly #1, Present System = 100

	ASSEMBLY #1	ASSEMBLY #2A	ASSEMBLY #2B
Purchased Materials	80.1	124.7	125.2
Present Assembly	<u>19.9</u>	<u>44.8</u>	<u>18.1</u>
Total	100.0	169.5	143.3

TABLE 3.2.2.2B

## PURCHASED MATERIALS, NOT Affected BY BLANKET ASSEMBLY COSTS

	ASSEMBLY #1	ASSEMBLY #2A	ASSEMBLY #2B
Cells	45.6	90.9	91.3
Coverglass	13.6	13.5	13.8
Other Direct Materials	11.4	11.4	11.4
Substrate	7.3	7.3	7.3
Tools & Fixtures	<u>2.2</u>	<u>1.6</u>	<u>1.4</u>
Subtotal	80.1	124.7	125.2

TABLE 3.2.2.2C  
ASSEMBLY COSTS USING PRESENT SYSTEM

	ASSEMBLY #1	ASSEMBLY #2A	ASSEMBLY #2B
Assembly Labor	11.0	24.8	10.0
Inspection & Test	2.8	6.2	2.5
Manufacturing Support	3.7	8.3	3.4
G&A	<u>2.4</u>	<u>5.5</u>	<u>2.2</u>
Subtotal	<u>19.9</u>	<u>44.8</u>	<u>18.1</u>

### 3.2.3 Projected Near Term Improved Manufacturing Capability, Rates and Costs

#### 3.2.3.1 Rates

In analyzing the capability of the present system to meet the manufacturing requirements, several process steps marginally capable of meeting the hypothetical production rate were uncovered. Specifically in Process Step One — Position and Weld Interconnects — the semi-automatic interconnect weld station must be operated at three shifts per day. For redundancy and reliability, a second station should be added, with one station operating two shifts; and the second one operating one shift. This way, should one machine break down, operators can be moved to another shift on the functioning machine to keep production going while the stopped machine is being repaired.

In Process Step Eight — Bond Module to Substrate — to accomodate the larger module the present machine base should be enlarged. This projected larger machine can apply adhesive to any of the several modules of this study in less than seven minutes per module. The newly introduced present machine has removed a labor-intensive bottleneck from the panel lay-up operation.

Other Near-Term improvements consist of improving work stations, increasing the rate of the glassing machine and other production aids, discussed in Section 3.1.

The production rate would improve to permit the assembly to be done on a two shift basis, including machine maintenance.

### 3.2.3.2 Cost

A comparative solar cell blanket production cost is presented in Table 3.2.3.2.

**TABLE 3.2.3.2 COMPARATIVE ASSEMBLY COSTS**

**TABLE 3.2.3.2. A TOTAL COST NEAR-TERM PARTIAL AUTOMATION**

	ASSEMBLY #1	ASSEMBLY 2A	ASSEMBLY 2B
● Purchased Material*	80.1	124.7	125.2
● Near Term Auto Assembly	<u>13.6</u>	<u>27.4</u>	<u>12.4</u>
● Total	93.7	152.1	137.6
● Savings over Present System	6.3	17.4	5.7

\* See Section 3.2.2.2 for detail

**TABLE 3.2.3.2 B NEAR-TERM PARTIAL AUTOMATION**

	ASSEMBLY #1	ASSEMBLY #2A	ASSEMBLY #2B
● Assembly Labor	7.5	15.1	6.9
● Inspect and Test	1.9	3.8	1.7
● Manufacturing Support	2.5	5.1	2.3
● G & A	<u>1.7</u>	<u>3.4</u>	<u>1.5</u>
● Subtotal	13.6	27.4	12.4

**TABLE 3.2.3.2 C NEAR-TERM PARTIAL AUTOMATION COST**

	ASSEMBLY #1	ASSEMBLY #2A	ASSEMBLY #2B
● Non-Recurring	0.9	0.8	0.6
● Recurring	0.2	0.2	0.2

As can be seen from the table, Near Term Automation reduces labor costs below the Present System by 31 to 39%.

### 3.2.4 Optimized Future Automation, Rates and Costs

By incorporating all the future improvements in the automated solar blanket process steps as discussed in Section 3.1, the result would lead to the Optimized Future Automated Manufacturing Capability. This future manufacturing capability is shown schematically in Figure 3.2.4.

#### 3.2.4.1 Rate

The production rate would enable the assembly to be accomplished on a one shift basis.

#### 3.2.4.2 Production Cost

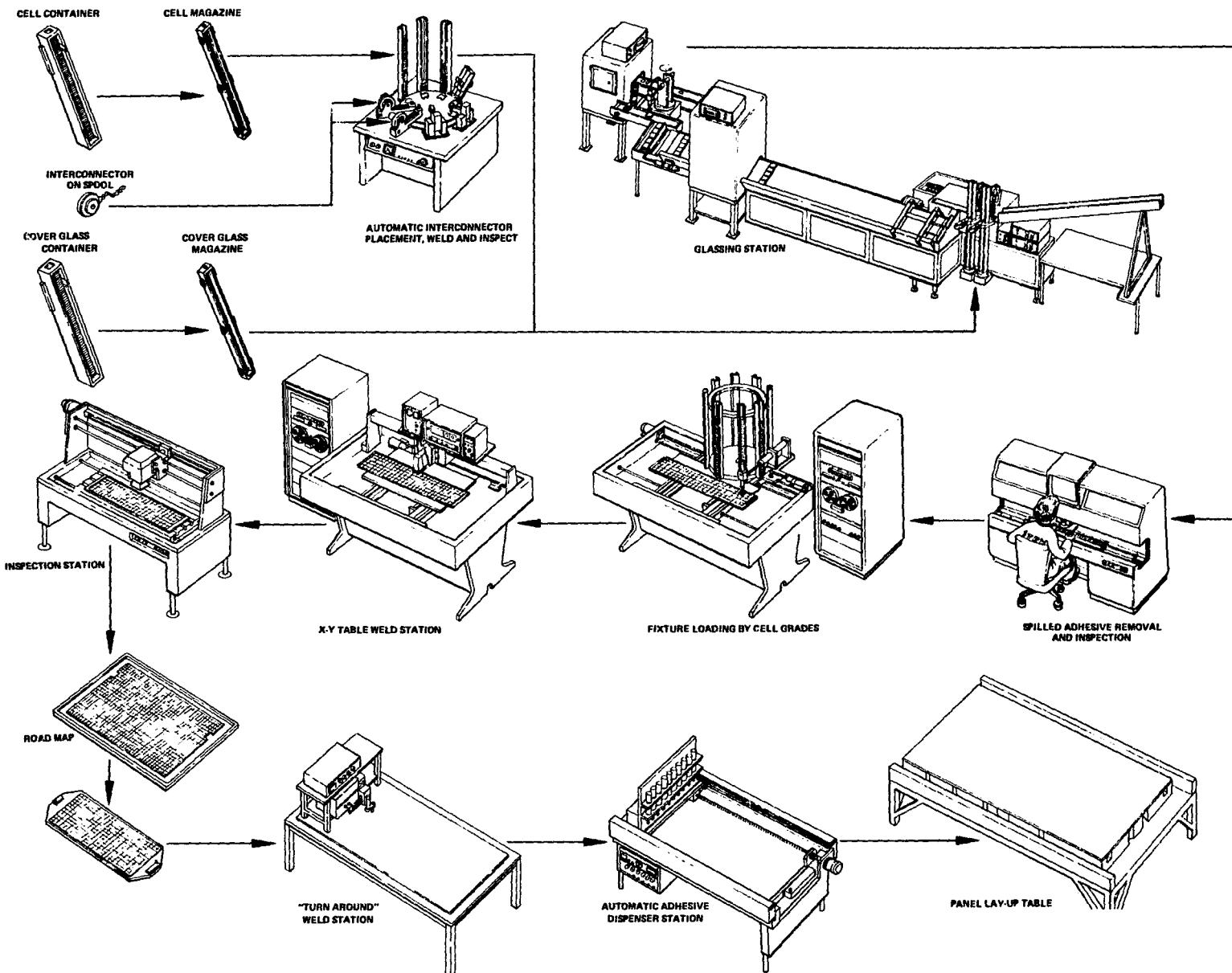
A comparative solar cell blanket production cost is presented in Table 3.2.4. All numbers, as in the case of the Near Term Automated Manufacturing Capability (Section 3.2.3.1) are normalized to 100= TOTAL COST of Assembly #1 - Present System.

TABLE 3.2.4.1 - COMPARATIVE SOLAR  
CELL BLANKET COSTS

#### 3.2.4.2 A TOTAL COSTS - FUTURE AUTOMATION

	Assembly #1	Assembly #2A	Assembly #2B
Purchased Material	80.1	124.7	125.2
Future Automated Mfg. Capability	6.4	12.9	5.7
TOTAL	86.5	137.6	130.9

FIGURE 3.2.4



FUTURE AUTOMATED SOLAR ARRAY ASSEMBLY LINE

**3.2.4.2 B - BREAKDOWN OF ASSEMBLY COST USING  
FUTURE OPTIMIZED MANUFACTURING CAPABILITY**

	Assembly #1	Assembly #2A	Assembly #2B
Assembly Labor	3.5	7.0	3.1
Inspection and Test	0.9	1.9	0.8
Manufacturing Support	1.2	2.4	1.1
G & A	0.8	1.6	0.7
	<hr/>	<hr/>	<hr/>
	6.4	12.9	5.7

**3.2.4.2 C - FUTURE OPTIMIZED AUTOMATION**

**SAVINGS ON ASSEMBLY COSTS**

Present System	19.9	44.8	18.1
Future Optimize	6.4	12.9	5.7
SAVE	<hr/>	<hr/>	<hr/>
	13.5	31.9	12.4

The savings in assembly cost with the Future Optimized Manufacturing Capability over the Present System as noted from Table 3.2.4.2 C were estimated to 68%, 71% and 69% for Assembly #1, Assembly #2A and Assembly #2B respectively.

**3.2.4.2 Automation Costs**

**TABLE 3.2.4.2 D AUTOMATION COSTS**

Non-Recurring	4.1	4.4	3.4
Recurring	1.0	1.1	0.9

### 3.3 Cost Benefit Analysis

Evaluation of each improvement was done on a cost benefit analysis basis. For this report Table 3.3.1 was prepared on a step-by-step basis, showing the investment cost and the resulting savings for the case of the "Future Optimized Automation". Again, because the dollar values are real, they have been normalized to be multiples of the annual total cost (1979) of one assembly worker.

Table 3.3.2 is a graphical presentation of the various cost elements using the Present System costs of each assembly as a function of cell area, which shows that assembly costs go down as cell area increases.

Table 3.3.3 shows that the material costs, present system, are strongly influenced by cell costs.

Table 3.3.4 shows graphically, based on costs of the present system, that the power-to-mass ratio improvements increase total costs, and that the optimum choice for a high ratio of power-to-mass at the lowest cost would be Assembly #2B using the  $3 \times 3 \times .005$  cm standard bar contact cell.

#### 3.3.1 Investment by Manufacturer

The results of analyzing the TRW present facility in its capability to meet the manufacturing requirement were presented in the previous sections. The results of the analysis indicated two levels of upgrading of the present capability could be made which would render correspondingly higher efficiency/lower costs in the manufacturing of large scale solar arrays. The related investment for the first level

TABLE 3.3.1

## COST - BENEFIT ANALYSIS FOR EACH PROPOSED AUTOMATED PROCESS

ASSEMBLY DESCRIPTION, CELL TYPE	DAILY CELL PROD. REQ'D.	COST OR SAVING <sub>3</sub>	WELD INTER-CONNECT TO CELL	INSPECT	ASSEM. GLASS TO CELL <sub>1</sub>	CLEAN CELL STACK <sub>1</sub>	INSPECT & MATCH CELLS	ASSEM. MODULES	INSPECT	BOND MODULES TO SUBSTRATE <sub>2</sub>	CLEAN PANEL	TEST & INSPECT	TOTALS
• ASSEMBLY #1 WRAP-AROUND CONTACT 2x4x0.02cm	3,600	INVESTMENT COST	-	-	4.6	1	1	6.2	1	0.2	-	-	14
		LABOR SAVING	-	-	3	7	2	9	3	0	-	-	24
• ASSEMBLY #2A STD CONTACT 2x2x0.05cm THIN CELLS	7,200	INVESTMENT COST	2.9	0.6	7.6	1	1	1	1	0.2	-	-	15.3
		LABOR SAVING	13	2	6	14	5	5	3	0	-	-	48
• ASSEMBLY #2B STD CONTACT 3x3x0.05cm THIN CELLS	3,200	INVESTMENT COST	2.9	0.6	4.1	1	1	1	1	0.2	-	-	11.8
		LABOR SAVING	9	3	3	6	2	8	2	0	-	-	33

1. Investment in glassing machinery reduces labor in cell stack cleaning as well.
2. This cost is for modifying the existing machine to handle modules of different over-all dimensions from present systems.
3. Cost and savings are expressed in multiples of the annual cost of one assembly worker.

## STUDY OF AUTOMATED MODULE FABRICATION FOR LIGHTWEIGHT - SOLAR BLANKET UTILIZATION

LABOR, MATERIAL AND TOTAL COSTS vs CELL SIZE, PRESENT SYSTEM

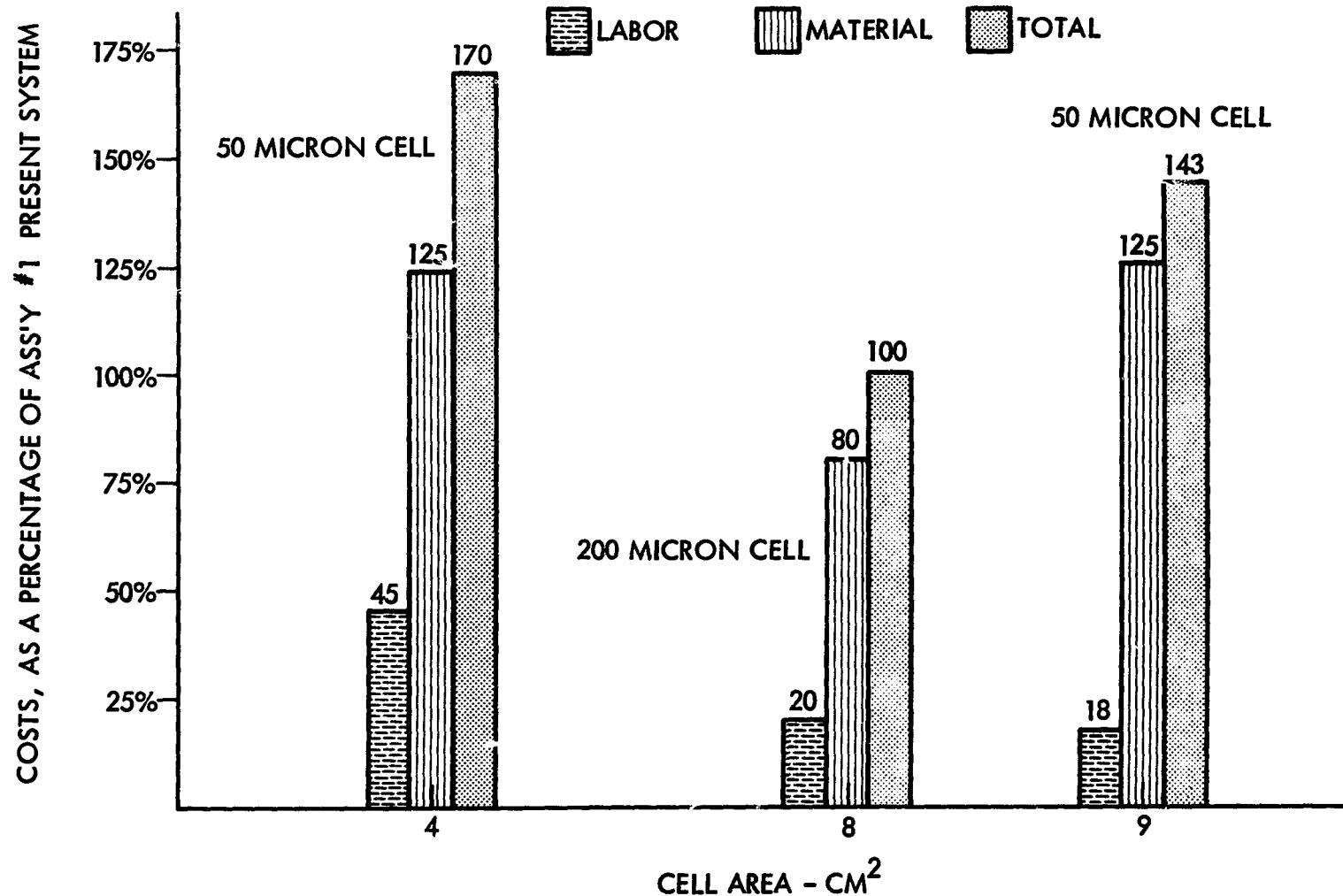
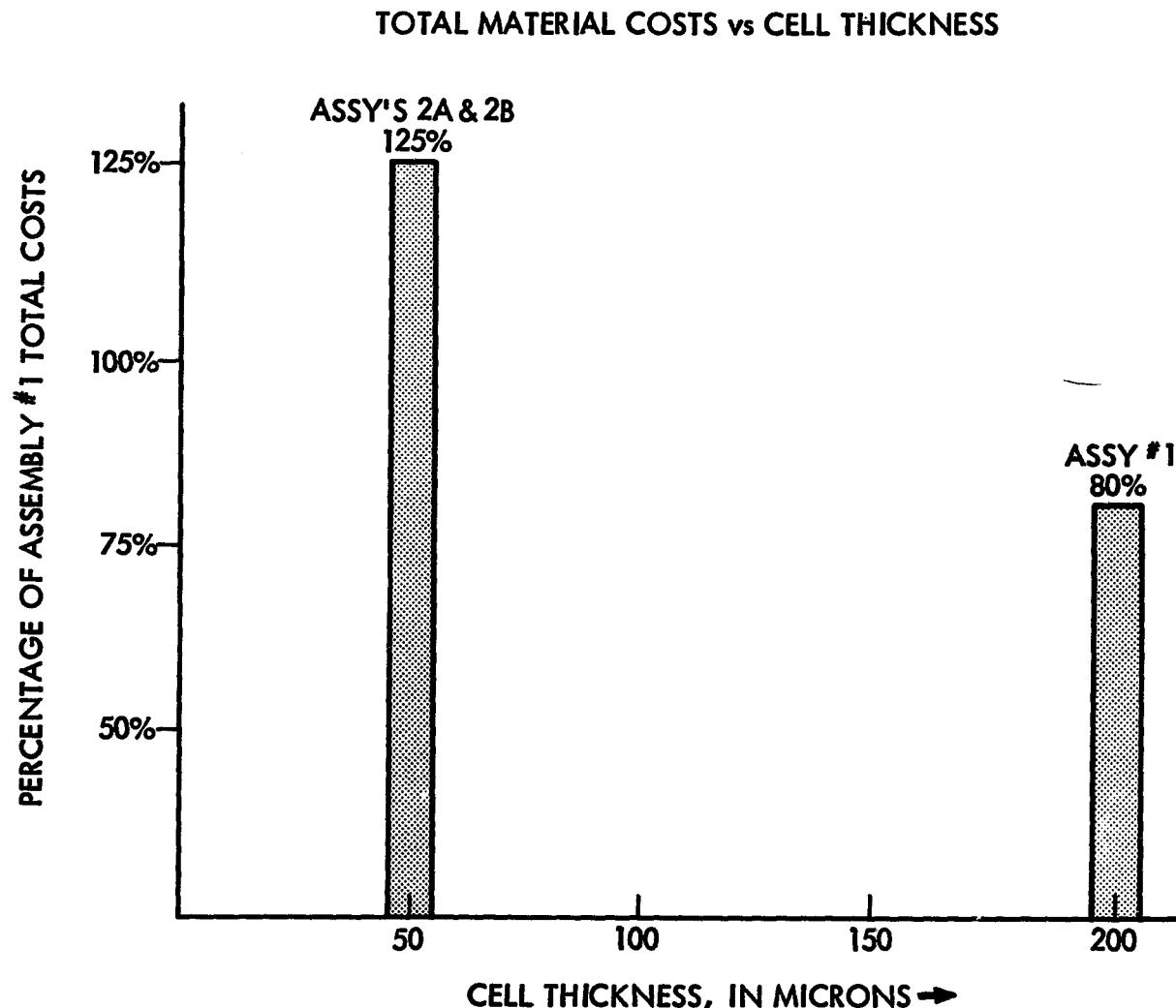
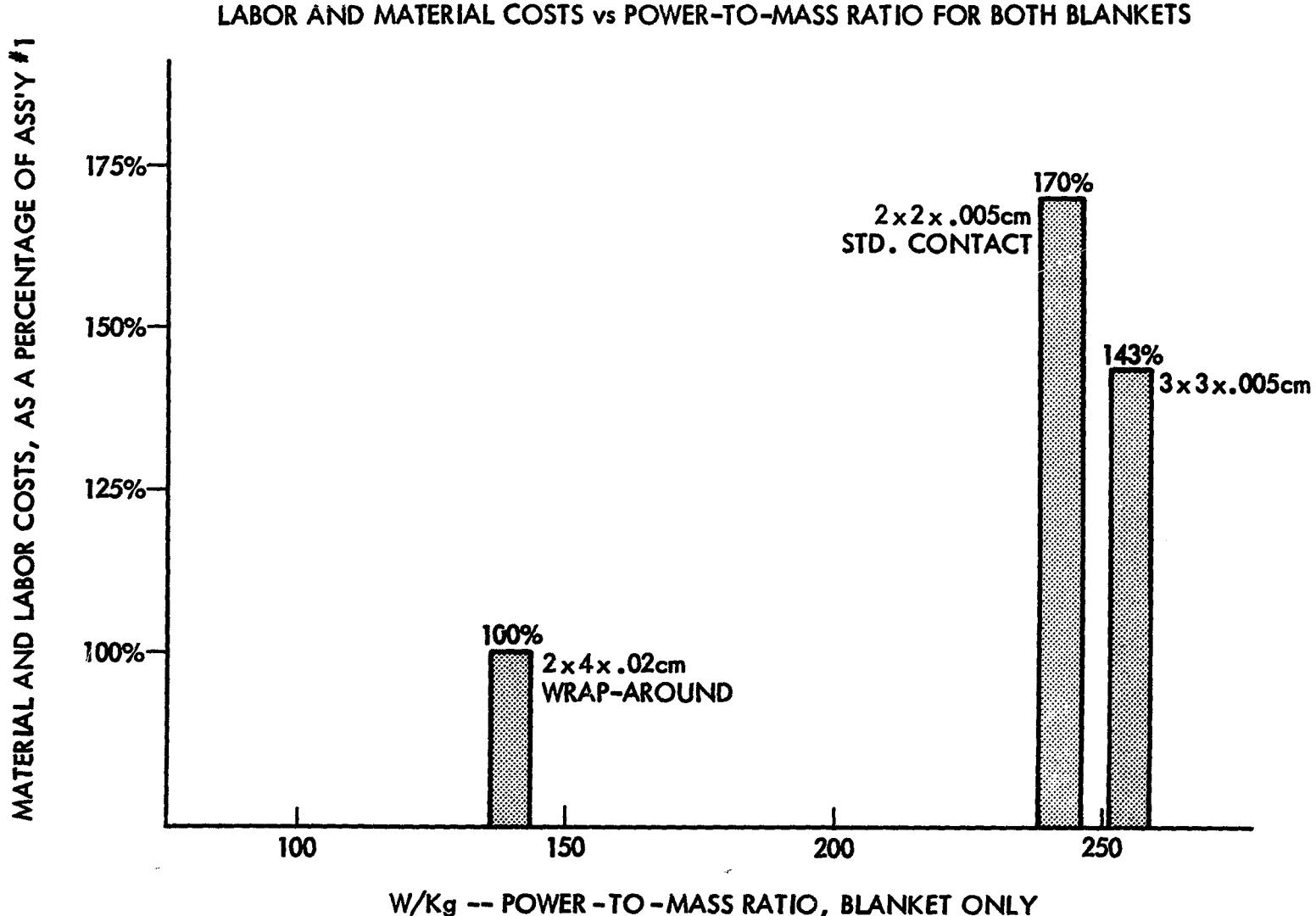


FIGURE 3-3-2

**STUDY OF AUTOMATED MODULE FABRICATION FOR  
LIGHTWEIGHT - SOLAR BLANKET UTILIZATION**



STUDY OF AUTOMATED MODULE FABRICATION FOR  
LIGHTWEIGHT · SOLAR BLANKET UTILIZATION



of upgrading was minimal, practically at the level normally spent for periodic equipment replacement. A modest capital investment is needed for the second level; in the range from one-half to one million dollars. The market size necessary to make such an investment cost-attractive to TRW - would be 50 kilowatts in eight months.

TRW is fully committed to the space solar array business; it has a long-term plan for extending automation of solar array manufacturing to meet growing market demands for production. Therefore, some of the automation described in this study will be undertaken without the specific driving force of the potential market described in this study.

### **3.4 Unresolved Problem Areas**

One unresolved problem uncovered by this study is in the area of in-process inspection. For assurance of long array life, a number of 100% inspections at in-process points are necessary. Additionally, statistically small samples are destructively tested, such as pull tests for measuring the ultimate strength of representative cell-interconnect joints. The high touch-labor content of the 100% inspections, plus the potential of undetected defects due to operator fatigue, make these operations prime candidates for automation.

The present principal mode of inspection is optical; the inspectors use optical comparators and stereomicroscopes.

Automatic optical inspection equipment is available in the marketplace. A preliminary survey of the equipment was performed as part of this study. The survey concluded that a much more extensive effort would be needed to select equipment which could be recommended for integration into

TRW's array assembly facility than the scope of this contract would permit. This problem is therefore under study by TRW's Product assurance group.

#### 4.0 CONCLUSIONS

It appears that the option which has the most appeal from power-to-mass ratio for the lowest cost is Assembly #2B, using the  $3 \times 3 \times .005$  cm cells.

- Automation of array manufacturing processes is cost effective. It reduces labor costs by more than its investment costs, even for larger area ( $3 \times 3$  cm) cells. For TRW, the incremental investment necessary to increase the degree of automation in the existing facility is extremely cost-effective.
- Automation, as defined in this study, must include automated process monitoring. Two benefits are (1) reduction in costs of inspection and rework and (2) increased array reliability.
- Automation widens the range of cost-effective production rates in a facility. The present capability at TRW was shown to be able to accommodate the very high production rates used in this study, and is operating effectively at its current level.
- Automation is almost mandatory for thin cells because attrition rates for human handling of these cells are quite high.

#### 5.0 RECOMMENDATIONS

It is recommended that cost-effective automation be implemented whenever large-scale space arrays are to be built in the future, not only

for the conclusions stated in Section 4.0, but additionally because promising new solar cell concepts are as thin as, or larger than, those studied in this project. In either case, automation will be practically mandatory to achieve acceptably low attrition rates. New thin cells are the Front Surface Field cell and the Thin Tandem Junction cell, both of which need to be 30 to 50 microns thick to be efficient. Larger cells are 5 x 5 x 0.02 cm standard bar contact cells.

An additional recommendation is that automated inspection methods must be studied and cost effectively incorporated into automated operations in order to maintain the high through-put and reliability required for fabrication of large arrays.

#### 6.0 NEW TECHNOLOGY

No new technology was identified during this study.

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